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ABSTRACT

Silicon carbide fiber-reinforced silicon carbide matrix (SiC/SiC) composite components were tested in an aircraft combustion environment using the Rich-burn, Quick-quench, Lean-burn (RQL) sector rig. To assess the condition of the SiC/SiC liners after combustor testing, their mechanical properties were measured. Specimens were machined from two of the sector rig components, the lean transition liners (LTLs) and the lean zone inner diameter liners (LZIDs) that were tested for various times to obtain post-exposure strengths. The average strength for the LTLs tested up to 260 hours was the same as average strengths obtained from witness coupons machined from the as-manufactured components. However, for the LZIDs, post exposure strength decreased with increasing exposure time. In addition, NDE results from the as-manufactured components were compared to post-exposure NDE. The techniques employed were able to image significant damage in these combustor liners that manifest itself as low post-exposure strength. The thermography and ultrasonic techniques were particularly effective in finding damage in the lean zone inner diameter liners.

INTRODUCTION

A silicon carbide fiber-reinforced silicon carbide matrix (SiC/SiC) composite is being evaluated for possible use as a combustor liner material in gas turbine engines for aircraft propulsion [1,2] and power generation [3–8]. SiC/SiC ceramic matrix composite is an excellent candidate for combustor applications, based on its thermal conductivity and high temperature capability [8,9]. Advanced materials such as SiC/SiC composites allow propulsion components to be fabricated that reduce or eliminate cooling air and thus allow higher gas temperatures. The elimination of film cooling with corresponding reduction in NOx formation allows the extra air to be used for other purposes, thus improving the efficiency of the engine. Data on the durability of SiC/SiC composites in the combustor environment is required to verify operational assumptions and validate design practices.

To test SiC/SiC components in a combustion environment, the Rich-burn, Quick-quench, Lean-burn (RQL) sector rig was developed at NASA Glenn Research Center under the High Speed Research/Enabling Propulsion Materials (HSR/EPM) program. The purpose of the sector rig was to demonstrate the structural durability of the SiC/SiC liners in a combustion environment where stresses, temperatures, and pressures would reflect the operating conditions found in an advanced turbine engine. A HSR program goal of 200 hours of rig operation at aircraft combustor conditions was completed [1,2].

Fifty-six hours of additional testing of SiC/SiC combustor liners were conducted in the RQL sector rig after the end of the HSR program, resulting in a total of 260 hours of hot exposure. All of the CMC liner components remaining in the rig after 260 hours of exposure were removed for post-test evaluation. The purpose of this paper is to compare the as-manufactured and post-test properties of two of the six combustor liner components, the lean transition liners and the lean zone inner diameter liners. Pre- and post-test mechanical properties are presented and compared to NDE results.

MATERIAL

Sector components were manufactured by Honeywell Advanced Composites from a SiC/SiC composite developed under the EPM program. A slurry-cast, melt-infiltrated SiC matrix was reinforced with Sylramic SiC fibers. The fiber tows were woven into 5-harness satin weave cloth. Fiber tow spacings of 18 and 22 ends per inch (EPI) were utilized to manufacture the parts, resulting in a nominal fiber volume fraction of 35 and 42%, respectively. More details on the material can be found in ref. 9.

RQL SECTOR RIG CONFIGURATION

Rig Description

The RQL sector rig was designed by Pratt & Whitney under the HSR program and was installed at NASA Glenn in 1998. The rig contains two rich zone liner cans transitioning to a 60° sector lean burn zone. Figure 1 is a schematic of the rig, along with images of the individual components. Six different SiC/SiC component geometries were designed and manufactured for the combustor liner. Table I contains a list of the number of parts required for a full liner set [1].

Figure 2 shows the upstream view of the RQL sector rig as seen from the lean zone. A fuel-rich mixture is ignited by the fuel/air nozzles and enters the rich zone liners. By-pass air is mixed with the burning fuel at the exit of the rich zone liner, resulting in a leaner fuel/air mixture at the entrance of the lean transition zone. Gas analysis capability exists downstream in the piccolo probe (not pictured), which also simulates the presence of the first stage turbine vanes that are normally downstream of the combustor in an aircraft turbine engine.

The Preheated Combustor and Materials Test Facility (PCMTF) in test cell CE-9 was used to conduct the RQL sector rig testing. The PCMTF provides 450-psig combustion air for advanced combustor and materials research, at a maximum flow rate of 14 kg/sec and temperatures up to 620 °C [10].

Table I – Summary of full SiC/SiC liner set for the sector rig.

Part Name	**Abbreviation**	**Liner Set Requirements**
Rich Zone Liner	RZL	2
Lean Transition Liner	LTL	12
Bulkhead Heatshield	BHHS	1 center + 2 halves
Lean Zone Inner Diameter Liner	LZID	6
Lean Zone Outer Diameter Liner	LZOD	3
Sidewall	Sidewall	2
		28

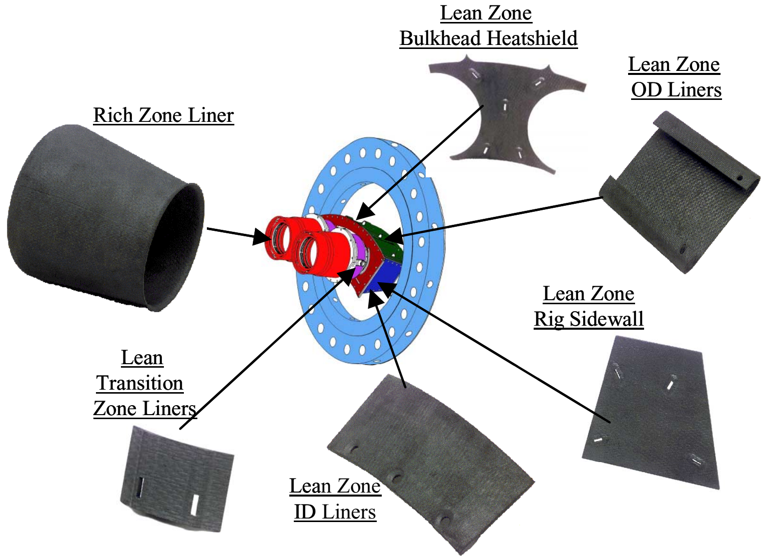


Figure 1 – Schematic of RQL sector rig and images of MI SiC/SiC component geometries.

Figure 2 – Photograph of the RQL sector rig. The view shows the lean zone, looking upstream toward the rich zone.

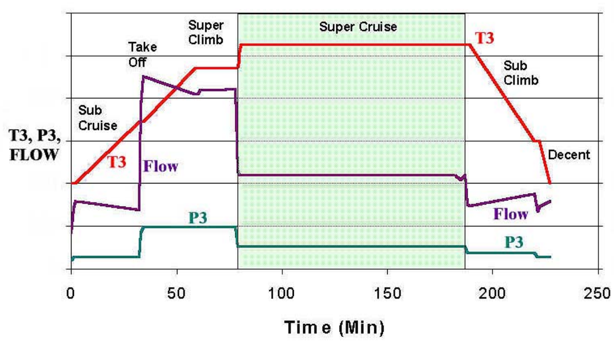


Figure 3 – Cycle used during sector rig testing.

Combustion Test Cycle

The test cycle used during the SiC/SiC sector rig operations is shown schematically in Figure 3. Air temperature (T3), pressure (P3), and flow rate were varied to approximate the anticipated service cycle of the HSCT engine combustor. All aspects of an HSCT flight operation, such as take-off, climb, cruise, and decent, are included in this cycle. Because of PCMTF facility constraints, the order of these operational segments was changed relative to actual operational sequence as shown in Figure 3.

SiC/SiC Components

In this study, the post-test properties of two of the six sector rig components were evaluated, the lean transition liner and the lean zone inner diameter liner. The lean transition liners (LTLs) are curved plates, about 33 mm wide (along the flow direction), covering a 60° arc (Fig. 1). Two build-up regions of 12-ply thickness reinforce the locations of the attachment holes, with 6 composite plies in the remaining regions. The LTLs are attached to the rig back structure with SiC/SiC Miller attachments [11]. A full set of lean transition liners consists of two cylindrical assemblies of six liners, for a total of twelve. The LTLs installed in the sector rig can be seen in Figure 2. A maximum part temperature of about 1250 °C occurred during the supercruise portion of the test cycle (Fig. 3).

The lean zone inner diameter liners (LZID) are also curved plates, each covering about a 30° arc of the total 60° sector lean zone (Fig. 1). A twelve-ply thick leading edge reinforces the attachment hole region. The rest of the LZID is six plies thick. These liners are about 53 mm wide along the flow direction and are held in place with three superalloy bolts. A full set contains two rows of three liners, the aft liners covering the attachment regions of the upstream liners as shown in Figure 2. The LZID temperature reached a maximum of 920 °C during sector rig testing.

Several CMC liners were removed from the sector rig after 115 hours to conduct post-exposure analyses [2]. The rig was reassembled and 145 hours of additional testing was conducted. In addition, a few liners were removed during rig operation when periodic inspections revealed potential damage. After completion of 260 hours of operation, the rig was disassembled and all MI SiC/SiC combustor liners were removed. As a result of these events, the LTLs available for evaluation were exposed for 56 to 260 hours. The LZIDs examined in this study were tested in the sector rig for 115, 145 or 260 hours. The parts evaluated are listed in Table II.

All the parts removed after completion of 260 hours of testing were inspected for damage. None of the lean transition liners or lean zone ID liners had any visually detectable damage.

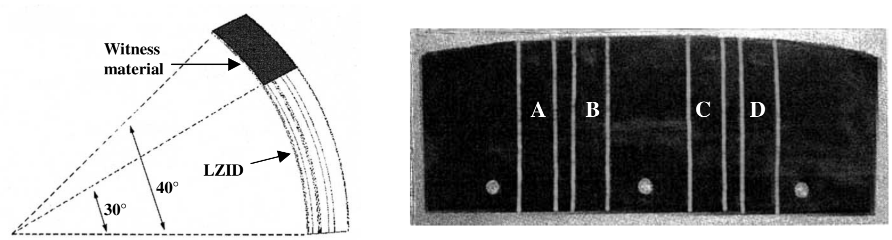
MECHANICAL PROPERTY MEASUREMENTS

Flexure coupons were machined from the as-manufactured and exposed sector parts to obtain mechanical properties. The as-manufactured parts were supplied with extra material that was machined into test coupons (Figs. 4 and 5). The exposed parts were machined to obtain test coupons of the same geometry as was used for the witness testing. Diagrams showing cutting diagrams for witness and post-exposure specimens are also shown in Figures 4 and 5. Two post-exposure specimens from each LTL and four from each LZID were machined and tested.

Table II – SiC/SiC liners evaluated for post-exposure properties.

Lean Transition Liner, part ID	**Exposure Duration (hrs)**	**EPI**
107-4, 107-3	56	22
100-3	62	18
102-2	115	18
105-2, 105-3, 109-1, 109-3	115	22
101-1, 101-2, 101-3, 101-4	145	18
107-1, 107-2	145	22
102-1	207	18
106-2, 106-4, 100-1	260	22
Lean Zone Inner Diameter Liner, part ID	**Exposure Duration (hrs)**	**EPI**
216-1	115	18
218-2, 208-2	115	22
215-1	145	22
216-2, 207-3	145	18
218-1, 205-2, 208-3	260	22

All part numbers have the prefix 555-07-xxx-x.



a. b.

Figure 4 – Locations of mechanical test coupons for lean zone inner diameter liners, a) schematic showing location of witness coupon, b) photograph showing location of post-exposure flexure coupons.

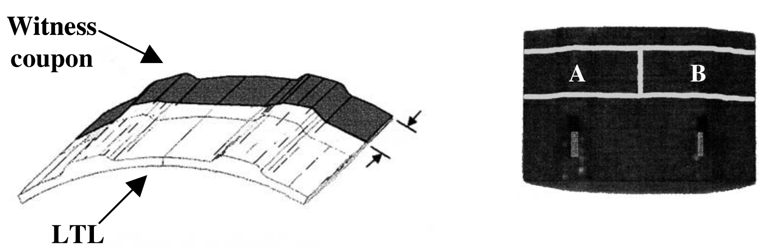


Figure 5 – Mechanical test coupons for lean transition liners, a) schematic showing location of witness coupon, b) photograph showing location of post-exposure flexure coupons.

Non-standard, 3-point flexural tests were conducted on coupons machined from both the LTLs and the LZIDs and are shown in Figure 6. Equations were developed to calculate the stress at failure for each specimen type. The formulations were based on specimen geometry and the failure mode [12]. Interlaminar shear failure of the LTL coupons occurred and the peak interlaminar shear stress $\tau_{r\theta}$ was calculated using the following:

$$\tau_{r\theta} = 1.5\ V(\theta)/bh \tag{1}$$

where b is the specimen width, h is the specimen thickness at the failure location, and V(θ) is the shear force distribution as a function of angular distance θ as shown in Figure 6a. V(θ) is given by

$$V(\theta) = M(\theta)/R\sin(\theta) \tag{2}$$

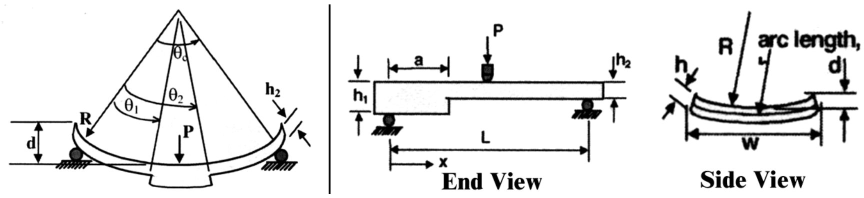
R is the inner radius of curvature of the coupon and M(θ) is the bending moment distribution. The formula used to determine M(θ) is

$$M(\theta) = PR/2 * (\sin(\theta_c/2) - \sin((\theta_c-2\theta)/2)) \tag{3}$$

P is the applied load at mid-span and θ_c is the arc of the LTL flexural coupon support span, about 30°. Failures occurred at the angular locations of the one of the two build-up regions, and therefore θ = 8 or 20°.

The LZID coupons failed due to bending loads. The maximum flexural stress, $\sigma_{max,}$ was computed using this relationship:

$$\sigma_{max} = Ph_2[I_1L^3 + 4a^3(I_2-I_1)]/[8I_1I_2L^2] \tag{4}$$



a. b.

Figure 6 – Flexural coupons for strength measurement of exposed combustor liners; a) lean transition liner specimen, b) lean zone inner diameter liner specimen.

L is the span between load reaction points, P is the applied mid-span load, and h_1 and h_2 are the thickness of the thin and thick sections of the beam, respectively, a is the length of the thick section of the beam. The moment of inertia I is given by

$$I = bh^3/12 \tag{5}$$

The moment of inertia for the thinner section of the specimen, I_1, is calculated using h_1. I_2 for the thick section is calculated using h_2. The specimen width is b.

All coupon testing was conducted at 815 °C. At this temperature, SiC/SiC composites can have a minimum strength due to pesting phenomena [13, 14].

NON-DESTRUCTIVE EVALUATION PROCEDURES

Components were inspected in the as-manufactured condition by Pratt & Whitney. Radiography and ultrasonic transmission techniques were used to document the condition of each component. NDE examination of the SiC/SiC liners after exposure in the sector rig was conducted at three locations; Pratt and Whitney, Argonne National Laboratory, and NASA Glenn Research Center. The NDE methods utilized to evaluate the parts after completion of sector rig testing included ultrasonic c-scans, radiography, and thermography. Conventional radiography and micro focus x-ray inspections were conducted.

For ultrasonic c-scan technique employed by Argonne, two transducers (one transmitter and one receiver) of 10 MHz, are placed on opposite sides of the parts during the scan. Ultrasonic c-scan evaluation of the parts at NASA was accomplished with a single 10 MHz focused transducer. The sender/receiver transducer sends the sound into the specimen and receives the back wall echo from the specimen. A commercial data acquisition device acquires the returning sound waves from the specimen. Displayed data represented changes in peak amplitudes of the back wall echo from the test specimen at different spatial locations.

A pulsed thermography system, with 3.6 kJ flash energy xenon lamps placed 24 inches from and at 45° angle to the specimen and with a line-scanned IR camera positioned 18 inches from the specimen, was used to collect 15 frames of 346 points per line for 236 lines at a frame rate of 6 frames per second. Temperature data was stored in full 12-bit dynamic range with a resolution. Details regarding the thermography techniques used by Argonne can be found in references 15.

RESULTS AND DISCUSSION

Properties for Lean Transition Liners

The maximum interlaminar shear strength of the LTL coupons at 815 °C as a function of exposure time is shown in Figure 7. The data is separated according to EPI (or fiber volume fraction). Based on the average strengths, there appears to be no effect of the exposure on the strength of the liners. LTLs fabricated from 18 and 22 EPI composites have similar strengths. Note that the scatter in the witness coupon data (0 hrs) approximately bounds the range in strengths obtained for the exposed LTLs. A comparison of the witness and post-exposure shear strengths for the individual LTLs is given in Figure 8. Liners that were tested for the same duration and are from the same batch, such as 109-1 and 109-3, are plotted together. In general, the witness and the post-exposure coupons have similar strengths. Several liners, such as 101-1, 101-2, 101-3, 101-4, 109-1 and 109-3, have higher post-exposure strengths than measured for their witness coupons. Also, three LTLs, 100-1, 105-2 and 105-3 have lower post-exposure strengths than strengths obtained through testing of witness coupons.

NDE data was obtained for fourteen of the eighteen exposed LTLs listed in Table II prior to machining into mechanical test coupons. In general, comparison of pre-test and post-test x-ray images revealed little change. Thermography and ultrasonic results for several LTLs had indications that can be associated with damage. Figure 9 compares the pre-test thermography and post-test thermal diffusivity and ultrasonic images of part 101-4. Note that the dark bands in the thermography and ultrasonic images are regions in the LTLs containing extra plies and as such are not indications of damage. In the thermography and ultrasonic images obtained after 145 hrs of combustion exposure, potential defects appear near the edges of the part.

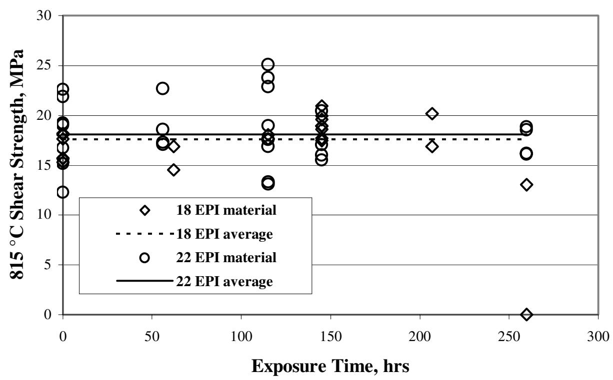


Figure 7 – Shear strength at 815 °C versus exposure time for lean transition liner coupons.

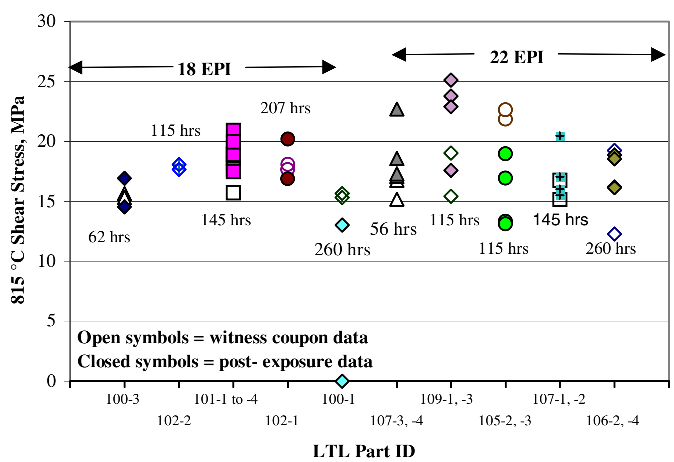


Figure 8 – Comparison of witness material and post-exposure shear strength of coupons machined from lean transition liners.

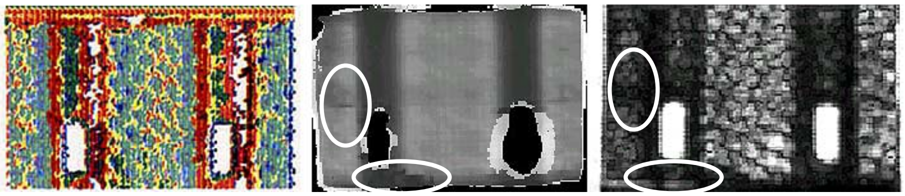
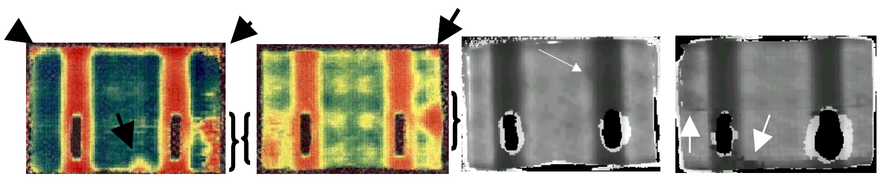


Figure 9 – NDE of lean transition liner 101-4, a) thermography of the as-manufactured liner, b) thermal diffusivity image after 145 hrs of combustion exposure, c) ultrasonic transmission image after 145 hrs. NDE indications in post-exposure images are circled.



a. 62 hrs (100-3) b. 115 hrs (102-2) c. 145 hrs (102-1) d. 260 hrs (100-1)

Figure 10 – Thermography images of lean transition liners subjected to various exposure times showing indications of potential damage. Part numbers are shown. Arrows and brackets indicate regions of damage.

Examples of thermography images of four LTLs that were sector rig tested for various times are shown in Figure 10. The NDE of all these liners revealed indications of potential damage. Of the 14 lean transition liners that were inspected after combustor rig testing, 8 had indications of damage in the NDE images. Six of these eight were fabricated from the lower volume fraction composite (18 EPI). In general, these indications all existed around the periphery of the liners.

A major concern for CMC combustor liner design is managing the thermal stresses [8,9]. The shear strength of the lean transition liners was generally unaffected by combustion exposure, suggesting that the LTL design minimized any thermal stress induced damage. However, NDE revealed indications of potential damage that generally exists around the periphery of the liners. It is possible that some of this damage is the result of contact between adjacent liners during rig operation, as the majority of indications are near edges that were bordering other combustor liners. Prior to the last 56 hrs of sector rig operation, two LTLs were removed when inspection revealed that one of the two fasteners holding each liner in place was broken [16]. For both of these liners, damage similar to that seen in the NDE image of parts 100-3 and 102-2 (Fig. 10) was visible. Finally, it is important to note that the NDE techniques employed were able to image significant damage that manifest itself as low post-exposure shear strength, such as for liner 100-1.

Properties for Lean Zone Inner Diameter Liners

A plot of 815 °C flexural strength for the LZID coupons is given in Figure 11. The data for each LZID is separated by EPI and exposure time. The average as-manufactured strength of the 18 EPI material is lower than that for the 22 EPI material. Although some scatter exists in the post-exposure data, a trend of decreasing strength with increasing exposure time can be seen. All LZIDs manufactured from the 18 EPI composite had debits in the post-exposure flexure strength relative to the witness coupon data after 115 and 145 hrs of combustor testing. The liners fabricated from the 22 EPI material had debits in strength only for the longest exposure time of 260 hours, while those exposed for 115 and 145 hours had higher average strengths after exposure.

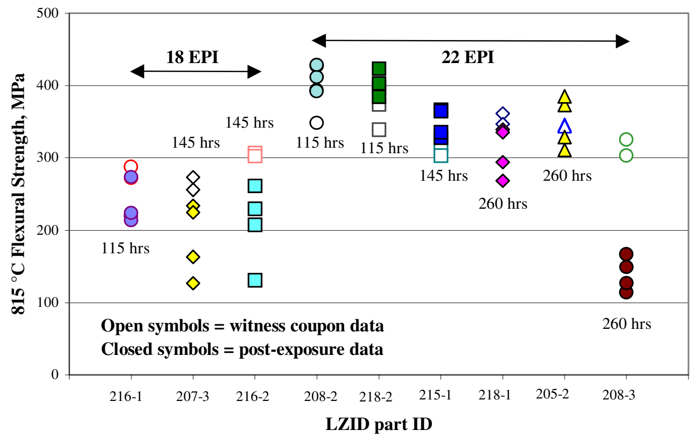


Figure 11 – Comparison of the 815 °C flexural strength of as-manufactured and post-exposed lean zone inner diameter (LZID) liner coupons.

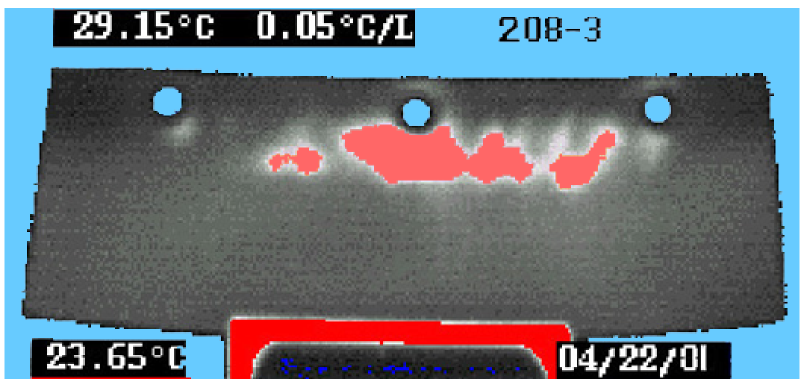


Figure 12 – Thermal wave image of LZID 208-3.

All lean zone ID liners were non-destructively examined after completion of sector rig exposure. Radiography revealed little change compared to baseline images. Through thermal and ultrasonic techniques, indications were found in all of the parts containing 38 % fiber volume fraction (18 EPI) and the 4 of 6 of the liners with 42% fibers (22 EPI). These four were those tested in the sector rig for the longest durations, 145 and 260 hours.

Thermal imaging was particularly effective in revealing locations of damage. An example is shown in Figure 12. Damage can be seen adjacent to the holes, in regions reinforced with 6 plies. This particular LZID was tested for 260 hrs, and had a significant reduction in flexural strength due to exposure (see Fig. 11).

For a few of the LZIDs manufactured from the 18 EPI composite, thermal images correlated with reductions in strength. In Figure 13, thermal diffusivity data is shown along with the flexural strengths obtained from the individual coupons. The locations of individual coupons are shown. The thermal diffusivity values are derived from changes in gray scale and thus are unit less. Thermal diffusivity obtained from good regions of the LZID was averaged to derive a mean thermal diffusivity, α_m. For regions with indications, as shown in the figure, the local thermal diffusivity value, α, was used to obtain ratios relative to the average of the undamaged regions, α/α_m. For this LZID, the post-exposure strength of the flexure coupons decreased with decreasing α/α_m.

Possible causes for damage in LZIDs include thermal gradient stresses, local compressive loading due to screws used to attach the liners to the back structure, vibratory bending loads due to aero-thermal forces during rig operation, or environmental attack in the combustion environment. Since NDE indications were generally observed around the center attachment hole and less prevalent in regions close to the two outer holes, it is unlikely that damage would be associated solely with fastening loads. Thus, thermal and bending fatigue may be responsible for the reductions in coupon strength and presence of damage as determined through NDE. Analyses based on rig boundary conditions are required to determine the stress components leading to part damage. Detailed microstructural examination of exposed parts may reveal the nature of damage in LZIDs, as well as the LTLs.

It is interesting to note that debit in flexural strength of the 18 EPI material occurred after the shortest exposure, 115 hrs, but for the 22 EPI material, strength reduction was measured only in LZIDs subjected to the longest exposure, 260 hrs.

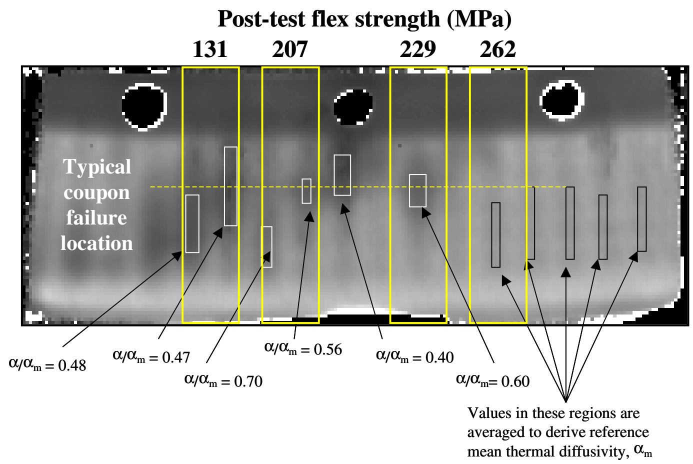


Figure 13 – Thermal diffusivity values for LZID 216-2. Locations of post-exposure flexure coupons are shown along with the resultant 815 °C strength values.

SUMMARY

Testing of SiC/SiC combustor liners in an aircraft gas turbine environment was conducted using the RQL sector rig. For the complete combustor liner set, six different SiC/SiC component geometries were designed and manufactured.

The post-exposure behavior of two of the six components was characterized. NDE techniques were employed to characterize tested parts. Shear and flexural strengths were obtained from coupons machined from the components. NDE and strength data obtained from the as-manufactured components was used to assess the post-exposure condition.

Based on the average strengths of coupons machined from lean transition liners that were tested in the sector rig for up to 260 hrs, there is no effect of the exposure time on the shear strength. For some of these combustor liners, NDE inspection revealed indications of potential damage that generally exists around the periphery of the lean transition liners. Parts with lower fiber volume (38%) tended to have more NDE indications than those fabricated from the higher fiber volume fraction composite (42%). The strength coupons were typically machined from regions where few NDE indications were found. In cases where NDE techniques imaged significant damage in regions used to make the test coupons, low post-exposure strength was observed.

The average as-manufactured and post-exposure flexural strengths of the lean zone inner diameter liners containing lower fiber volume fraction (18 EPI) are lower than that for the higher fiber volume fraction combustor liners (22 EPI). A trend of decreasing strength with increasing exposure time was found for coupons machined from lean zone inner diameter liners. Debit in flexural strength of the 18 EPI material occurred after the shortest exposure, 115 hrs, but for the 22 EPI material, strength reduction was measured only in LZIDs subjected to the longest exposure, 260 hrs. Thermal imaging was particularly effective in revealing locations of damage. For some lean zone inner diameter liners, thermal images correlated with reductions in strength.

The NDE techniques employed were able to image significant damage in these combustor liners that manifest itself as low post-exposure strength. The thermography and ultrasonic techniques were effective in finding damage in the lean zone inner diameter liners. Further analyses, such as microstructural examination, are required to characterize the nature of the damage.

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Silicon carbide fiber-reinforced silicon carbide matrix (SiC/SiC) composite components were tested in an aircraft combustion environment using the Rich-burn, Quick-quench, Lean-burn (RQL) sector rig. To assess the condition of the SiC/SiC liners after combustor testing, their mechanical properties were measured. Specimens were machined from two of the sector rig components, the lean transition liners (LTLs) and the lean zone inner diameter liners (LZIDs) that were tested for various times to obtain post-exposure strengths. The average strength for the LTLs tested up to 260 hours was the same as average strengths obtained from witness coupons machined from the as-manufactured components. However, for the LZIDs, post exposure strength decreased with increasing exposure time. In addition, NDE results from the as-manufactured components were compared to post-exposure NDE. The techniques employed were able to image significant damage in these combustor liners that manifest itself as low post-exposure strength. The thermography and ultrasonic techniques were particularly effective in finding damage in the lean zone inner diameter liners.

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